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THE SOLAR SYSTEM BORON ABUNDANCE*

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ABSTRACT

The concentrations of B in seven carbonaceous chondritic meteorites have been determined by the use of two different analytical techniques. The data correspond to a B/H ratio of about 10^{-9} compared to the value of 10^{-8} previously proposed by Cameron, Colgate, and Grossman. However, the meteoritic abundance remains at least a factor of 2–10 higher than various estimates of the solar photosphere abundance. We conclude that both meteoritic and photospheric B and Be abundances must be considered in comparisons with nucleosynthesis calculations. Using our revised B abundances and assuming ^{7}Li was synthesized in the big bang, we find that the residual ^{6}Li/^{10}B, ^{9}Be/^{10}B, and ^{11}B/^{10}B abundance ratios are well matched by the production rates for bombardment of a CNO mixture of solar proportions by protons and α-particles with a kinetic energy per nucleon spectrum of the form $E^{-1.8}$.

Subject headings: abundances — meteors and meteorites — solar system: general

I. INTRODUCTION

The typical good agreement between solar photospheric abundances of nongaseous elements and abundances derived from analyses of carbonaceous chondritic meteorites (Anders 1971; Ross and Aller 1976) is readily understood in terms of contemporary ideas of chondrite formation (see, e.g., Grossman and Larimer 1974). Carbonaceous chondrites resemble the solid material expected when a gas cloud of solar composition cools to temperatures of $\sim$300 K at low pressure (10^{-4} to 10^{-6} atmospheres). Thus, elements which are gases (CNO, rare gases, and perhaps Cl) are depleted in meteorites relative to the Sun. However, cases where elements are enriched in meteorites provide important information. For example, the 200-fold enrichment of Li (Nichiporuk 1971; Grevesse 1968) indicates thermonuclear destruction of solar Li, either in an earlier, totally convective, phase of solar evolution or by burning at the base of the surface convection zone during the main-sequence lifetime. Measurements of boron in the solar photosphere (Hall and Engvöld 1975; Kohl, Parkinson, and Withbroe 1977), the interstellar medium (Morton, Smith, and Stecher 1974), and Vega (Boesgaard *et al.* 1974) imply B/H $\approx 10^{-10}$ while Cameron, Colgate, and Grossman (1973) calculated a meteoritic B/H $= 1.5 \times 10^{-8}$ based on carbonaceous chondrite data from Quijano-Rico and Wänke (1969). Several papers concluded that boron is enhanced in carbonaceous chondrites and thus that these meteorites do not provide a valid solar system abundance for this element (Hall and Engvöld; Morton, Smith, and Stecher; Boesgaard *et al.*). The B concentrations obtained by Quijano-Rico and Wänke for ordinary chondrites suggest that B was in a volatile form in the solar nebula. Since ordinary chondrites are known to be depleted in moderately volatile elements, these chondrites cannot be used for estimating the solar system abundance, although Audouze, Lequeux, and Reeves (1973) proposed their use on a strictly ad hoc basis.

As emphasized by Cameron, Colgate, and Grossman (1973), a B/H value of 10^{-8} is too high to be compatible with otherwise attractive theories of galactic cosmic ray (GCR) nucleosynthesis of Li, Be, and B (Reeves, Fowler, and Hoyle 1970; Meneguzzi, Audouze, and Reeves 1971). The lower value of 10^{-10} has been generally accepted as more compatible with GCR nucleosynthesis; however, as discussed later, the high implied Li/B presents difficulties.

In view of the large difference between the meteoritic and solar B abundances and the implications for the nucleosynthesis of Li, Be, and B, we have made additional measurements of the meteoritic B abundance.

II. EXPERIMENTAL

We have used two different methods: (1) track counting and (2) beta counting. (1) Tracks are produced in cellulose nitrate plastic by α-particles from the ^{10}B(n, α) reaction. The plastic is clamped to a homogenized pellet, irradiated with thermal neutrons, and then chemically etched to reveal cone-shaped tracks. The measured track density relative to a standard gives the B concentration. Corrections (ranging up to 30%) are made for background tracks from ^{17}O(n, α), ^{6}Li(n, α), and fast neutron recoils. (2) We produce ^{12}B with the reaction ^{11}B(d, p). The β-decay energy (13 MeV) and half-life (20 ms) of ^{12}B provide a unique decay signature. The meteorite is irradiated in 30 ms pulses with 2.8 MeV deuterons. After a short delay, betas greater than 6 MeV are counted in four 15 ms counting periods using a plastic scintillator. The ^{11}B concentration is proportional to the difference between the counts in the first two counting periods and those in the second two.

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Absolute concentrations for both track and beta counting measurements are based on National Bureau of Standards glass SRM 610. Some comparative measurements indicate that there are no systematic differences greater than $\sim 10\%$ in B concentration by the two methods, and this is not important for the questions addressed in this paper. A more detailed description of the experimental methods and results will be published elsewhere (Weller *et al.* 1977).

III. RESULTS

Table 1 summarizes the B concentrations obtained for individual meteorites. The track results (tx) for Haripura and Orgueil in Table 1 are given as upper limits because we had no control over sample preparation. These samples were powders prepared by Gopalan and Wetherill (1970). We have not tabulated track results for other meteorites which gave high (5–15 parts per million [ppm]) values and exhibited nonuniform B distributions indicative of contamination. The Haripura and Orgueil limits are given because they are low enough to be interesting.

All meteorites in Table 1 are carbonaceous chondrites. Our results for Lancé and Murray are distinctly lower than the 6.4 and 9.4 ppm, respectively, reported by Quijano-Rico and Wänke.

The final column in Table 1 gives the atomic B/H ratio calculated using Si as an intermediate normalization: $(B/H) = (B/Si)_{met}(Si/H)_{Sun}$. We have used Si contents for individual meteorites when possible; otherwise, average Si contents for the various C subgroups were used (Mason 1971). We adopt $(Si/H)_{Sun} = 4.5 \times 10^{-5}$ (Ross and Aller 1976). The progression between B/H in the C3, the C2, and the C1 meteorites is close to the 0.4/0.55/1 progression normally observed for C3/C2/C1 meteorites (Grossman and Larimer 1974). Our results indicate a B/H ratio which is different from both the 10^{-8} proposed by Cameron, Colgate, and Grossman (1973) and the 10^{-10} upper limit for the solar photosphere obtained by Hall and Engvöld (1975).

TABLE 1

B Concentrations in Carbonaceous Chondrites

Chondrite	Number of Samples Analyzed	ppm B*	(B/Si) (Si/H) (10^{-9})
C3:			
Allende, tracks (tx).	3	1.0 ±0.1	<0.75
Allende, betas (β). .	4	1.28±0.31	
Lancé (β).	2	1.46±0.56	0.84
C2:			
Murray (β).	5	1.18±0.25	1.1
Murchison (β).	7	1.41±0.26	1.3
Haripura (tx).	1	≤1.0	≤0.9
C1:			
Ivuna (β).	2	2.7 ±0.3	3.1
Orgueil (tx).	1	≤1.8	≤2
Orgueil (β).	2	1.58±0.14	1.8

* ppm = micrograms B per gram meteorite; errors are average deviations of individual sample analyses.

From our data, we propose a meteoritic solar system value of $B/H = 2 \times 10^{-9}$. Our abundance is a factor of 5 above the photospheric abundance given by Kohl, Parkinson, and Withbroe (1977) but is only a factor of 2 above the upper error bound given by Kohl *et al.*

The principal difficulty with B analysis is that there are serious contamination problems. All results are based on analyses of freshly prepared and cleaned surfaces. To minimize contamination, we carefully selected the meteorite samples analyzed and minimized the time between sample preparation and analysis. It is conceivable that our results are simply upper limits, but the following arguments indicate they are actual B concentrations. Recall that the important question is whether B/H is 10^{-8} or 10^{-10}. (1) Low B control samples (graphite, SiO_2 glass, and single crystal calcite) were analyzed in parallel with the meteorites. These samples showed consistently lower B concentrations than the meteorites. (2) The time between sample preparation and analysis and the total exposure time of the sample to the laboratory atmosphere were deliberately varied in the beta counting experiments. For samples prepared within 24 hours of analysis, contamination is not significant. (3) The track data indicate that the B was uniformly distributed on a 0.1 mm scale over the sample as expected for B from the meteorite, whereas the B distribution on a badly contaminated sample was often very nonuniform. Duplicate track analyses of 40 mg aliquots were always in good agreement. (4) After analysis, a Murchison sample was scraped twice with a SiO_2 chisel and the fresh surfaces reanalyzed without atmospheric exposure. All three measurements gave boron concentrations of 1.4 ± 0.2 ppm, indicating no surface contamination.

IV. DISCUSSION

Given our revised meteoritic abundance ($B/H = 2 \times 10^{-9}$) and the photospheric value of Kohl, Parkinson, and Withbroe (1977) of 4×10^{-10}, the factor of 100 discrepancy between the photospheric and meteoritic B abundances which previously existed in the literature has been reduced to a factor of 5. If the upper error limit of the Kohl *et al.* measurement is considered, the difference with the meteoritic abundance can be reduced to a factor of 2. The photospheric upper limit ($B/H < 2 \times 10^{-10}$) cited by Hall and Engvöld (1975) remains distinctly lower than our result or that of Kohl *et al.* However, taking all observations at face value it still appears that the photospheric B abundance is lower than the meteoritic abundance by a factor of 2–10. Independent of specific theoretical considerations about Li Be B nucleosynthesis, there are still several alternative interpretations: (1) If all observational data are correct and if these elements have not been depleted in the Sun by thermonuclear processes, the photospheric abundances must be adopted as the average solar system abundances. It can never be ruled out that a specific element has been anomalously enriched during the formation of carbonaceous chondrites. Such enrichment of boron or any other element would be cosmochemically unique and of great interest since the mechanism for this enrichment is not apparent. There has been considerable discussion of an apparent overabundance of Hg in carbonaceous chondrites (e.g., by Audouze, Lequeux, and Reeves 1973); but, given the amount of Hg in man's environment, we think a more detailed evaluation of the quality of the samples used for Hg analysis is required before the Hg overabundance is accepted. The conclusion that B was in a volatile form in the solar nebula must also be reconsidered. In any case, a reexamination of B concentrations in other types of chondrites seems appropriate, as well as a study of the distribution of B within individual meteorites. (2) The validity of the carbonaceous chondrite B abundance as a solar system average should be kept as a viable option. This requires explaining why the astrophysical abundances are lower. The solar B abundance upper limit of Hall and Engvöld is based on infrared B I transitions, whereas the interstellar (Morton, Smith, and Stecher 1974) and Vega (Boesgaard *et al.* 1974) observations used the B II resonance line in the far-ultraviolet (1362 Å) and the Kohl *et al.* photospheric result is based on rocket-UV observations at 2497 Å. It is possible that there are systematic differences (e.g., in *gf*-values) for these different lines. However, except for Kohl *et al.*, none of the above papers discusses the quality of the *f*-values used; in view of the uncertainties which have existed in the past, additional laboratory *f*-value measurements would be desirable. Further, independent of theories of nucleosynthesis and galactic evolution, it cannot be assumed that the B abundance for the interstellar gas or for Vega should be the same as for the Sun. The chief difference of interest is between the meteoritic and solar photospheric abundance. (3) An interesting alternative is that the anomalous abundance measurement is not B, but Be (Cameron, Colgate, and Grossman 1973). Our evaluation of new meteorite Be analyses by Quandt and Herr (1974) would yield Be/H $= 4 \times 10^{-11}$ in contrast to the generally accepted photospheric abundance of 1×10^{-11}. Thus, thermonuclear depletion of Be and B as well as Li in the Sun cannot be totally dismissed. However, if B were depleted by a factor of 5–10, one might expect a depletion of Be much larger than a factor of 4. The photospheric Be abundance is based on Be II lines around 3130 Å which is in a very complex region of the solar spectrum. Perhaps the identification of these lines or the effects of blending of interfering lines should be reexamined. We would also like to see an authoritative discussion of the accuracy of the Be II *f*-values. (4) The data are compatible with the meteoritic abundances of both B and Be being about a factor of 5 higher than the corresponding photospheric values. This suggests the possibility of an inhomogeneous solar photosphere in which a fraction, x, of the photospheric material has been subjected to high temperatures (e.g., by deep convective overturn) and has been totally depleted in Li Be B. The remaining $(1 - x)$ of photospheric material has been depleted in Li (e.g., by only shallow convective mixing) but not in B or Be. For $x \sim 0.8$, the photospheric B/H and Be/H would be a factor of 5 below the true solar system value, but B/Be would be correct. (5) Our own results may be upper limits due to contamination. Although we have already presented arguments against such an interpretation, it would be desirable for our abundances to be confirmed by additional B measurements on chondrites, preferably by a technique which analyzes samples with a smaller surface-to-volume ratio and which is thus less sensitive to surface contamination. Such a method, based on γ-rays from $^{10}B(n, \alpha)^7Li^*$, has been used by Curtis, Gladney, and Jurney (1976), and their initial results appear compatible with ours.

In summary, we conclude that at present both meteoritic and photospheric Be and B abundances must be considered in assessing theories for the nucleosynthesis of these elements. If subsequent work confirms the accuracy and applicability of the photospheric values, those from meteorites would have to be considered irrelevant.

V. IMPLICATIONS FOR Li Be B NUCLEOSYNTHESIS

Table 2 summarizes our adopted "solar" and meteoritic Li Be B abundances. As is customary, we assume that Li has been depleted in the Sun by thermonuclear processes; consequently the meteoritic Li is used in both sets of abundances. A survey of the present literature indicates that the number of proposed mechanisms for light-element nucleosynthesis exceeds the number of nuclei involved; consequently, it seems profitable only to seek the simplest mechanism which can explain the observed abundances in an astrophysically consistent manner. It is reasonable to assume the validity of the big bang and the accompanying nucleosynthesis of D, ^3He, and ^7Li (Wagoner, Fowler, and Hoyle 1967). Given the relative abundances of D and B, it is difficult to synthesize them in a single process. Further, calculations using very low-energy particle fluxes have not been able to satisfactorily produce $^7Li/^6Li$ ratios as high as the solar system value of 12.5 (see, for example, Bodansky, Jacobs, and Oberg 1975; Roche *et al.* 1976). Consequently, we shall focus on the remaining four nuclei: ^6Li, ^9Be, ^{10}B, and ^{11}B. We consider the simplest synthesis: spallation of CNO nuclei by protons and

TABLE 2

"SOLAR" AND METEORITIC Li Be B ABUNDANCES (units of 10^{-11})

Ratio	"Solar"	Meteoritic
Li/H......	200*	200*
Be/H......	1†	4‡
B/H.......	≤ 20§	200‖

* Nichiporuk 1971. The meteoritic value is taken for the "solar" nebula because of the presumed depletion of Li in the sun.

† Grevesse 1968.

‡ Quandt and Herr 1974.

§ Hall and Engvöld 1975.

‖ This work.

α-particles, e.g., irradiation of the interstellar medium by galactic cosmic rays as first discussed by Reeves, Fowler, and Hoyle (1970).

We first consider the spectral shapes compatible with the two sets of *relative* abundances and later consider the required particle fluences (integrated fluxes), since the fluences depend on spectral shape. The above four nuclei define three abundance ratios: ^{6}Li/^{10}B, ^{9}Be/^{10}B, and ^{11}B/^{10}B. Clearly, with only three numbers to fit, only simple theories can be considered. Further, the three ratios should not be given equal weight in assessing an acceptable fit. The ^{11}B/^{10}B isotopic ratio is precisely known, and *any calculation which fails to reproduce it to within ±0.1 is unacceptable.* In contrast, the ^{6}Li/^{10}B and ^{9}Be/^{10}B are elemental ratios, and to reproduce these to within a factor of 2 is quite acceptable. Table 3 compares the meteoritic and solar abundance ratios with spallation production rate ratios from Roche *et al.* (1976). The following discussion assumes that all relevant spallation cross sections are known with sufficient accuracy. Because the cross sections are constant at high energies, the abundance ratios in this energy range are unaffected by the spectral shape. Observations imply that the GCR spectrum above ~0.5 GeV is represented by a total energy power law. However, due to solar modulation, the GCR spectral shape cannot be determined at energies below 100 MeV per nucleon where it has the greatest effect on the abundance ratios. Results of two low-energy spectra are shown in Table 3: extrapolation of the total energy power law which has been adopted in many recent papers as a representation of the interstellar GCR spectrum, and a power law in kinetic energy per nucleon. For the latter spectrum, the exponent of 1.8 is chosen to fit the ^{11}B/^{10}B isotopic ratio; and, when this is done, excellent agreement is obtained with the revised *meteoritic* ratios. The total energy power law provides an acceptable fit to the meteoritic elemental ratios, but fails to match the boron isotopic ratio. This observation is not new to us, but its importance appears to have been underemphasized previously. Table 3 also shows that it is much more difficult to describe the "solar" abundances, particularly the high ^{6}Li/^{10}B ratio.

TABLE 3

COMPARISON OF RELATIVE ABUNDANCES AND SPALLATION PRODUCTION RATES*

Parameter	^{6}Li/^{10}B	^{9}Be/^{10}B	^{11}B/^{10}B
Spectral shape:†			
$(1 + E)^{-2.6}$	1.0	0.16	2.0
$E^{-1.8}$‡	0.46	0.09	4.0
Abundances:§			
"Solar"	≥ 5	≥ 0.3	4.0
Meteoritic	0.4	0.1	4.0

* Taken from Roche *et al.* 1976; includes both proton and alpha spallation for a CNO mixture of relative abundances = 3/1/5 by number.

† E refers to kinetic energy per nucleon.

‡ Exponent chosen to fit ^{11}B/^{10}B value.

§ See Table 2.

Consideration of a wider variety of spectral shapes (Roche *et al.* 1976; Meneguzzi, Audouze, and Reeves 1971) does not alleviate this difficulty. Thus, we conclude that the meteoritic relative abundances are more compatible with simple spallation synthesis than are the "solar" abundances. This point has not been considered in most recent astrophysical papers which have tended to focus on the B/H ratio; however, it has been noted in papers written by nuclear physicists (Roche *et al.*; Bodansky, Jacobs, and Oberg).

Because of the low threshold for ^{11}B production by ^{14}N(p, α), particle fluxes down to 5 MeV per nucleon must be considered in estimating the required particle fluences. For the $E^{-1.8}$ spectrum, we estimate that a total fluence of 3×10^{19} particles per cm^2 greater than 5 MeV per nucleon is required to produce the abundances shown in Table 2.

The basic question which remains is whether our proposed $E^{-1.8}$ spectrum can be ruled out on astrophysical grounds. Again we invoke our, perhaps Neanderthal, point of view that this problem is scientifically useful (and interesting) only if it is relatively simple. Specifically, if synthesis of these four nuclei is *not* possible with an *interstellar* GCR spectrum approximately like that of the present-day GCR (both in intensity and in spectral shape) interacting with an interstellar medium of approximately the same density and composition as observed today, then the problem appears open-ended. Previous studies beginning with Reeves, Fowler, and Hoyle (1970) show that there is no basis for ignoring the GCR contributions if the properties of the GCR and the interstellar medium were the same in the period prior to the formation of the solar system as they are today. Thus, if GCR nucleosynthesis fails, there are two alternatives: (1) the GCR and/or the local interstellar medium were very different before 4.5×10^9 yr ago or (2) a variety of sources and mechanisms (supernova shock waves, solar system synthesis, selective thermonuclear destruction, etc.) are contributing to the abundances of these four nuclei in addition to GCR nucleosynthesis. Case 2 is mundane and uninteresting; requiring two sources to explain the abundances of four nuclei is basically an admission of defeat. But, because case 2 is possible, case 1 or any other interesting variation can *never* be established. Returning to the question of the plausibility of an $E^{-1.8}$ spectrum, the crucial question is then: Could the present-day GCR spectrum be of this form? The demodulated GCR spectrum of Goldstein, Fisk, and Ramaty (1970) considered by Meneguzzi, Audouze, and Reeves (1971) has the form of the total energy power law in Table 3 and does not fit the solar system B isotopic ratio. Therefore, if this form of demodulated spectrum is correct, we have reached the logical stalemate discussed above. If it is not, and something similar to an $E^{-1.8}$ spectrum could be valid, it would be appropriate to face additional problems such as the heating of the interstellar medium.

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